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Theoretical Evaluation of Structural Insulated Panel Walls in Baltic Climatic Conditions

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Abstract

The reduction of construction costs as needed to increase construction productivity forces to the introduction of alternative construction solutions. Thus, the share of structural insulated panels for single-family houses is increasing. Despite the fact it is a widely used technology in the USA, there is a significant information gap for safe application in Baltic climatic conditions. The dynamic hygrothermal simulations DELPHIN was used to evaluate risks of mold growth and interstitial condensation. The city of Riga was selected to evaluate the hydrothermal performance of SIP panels. The different indoor air parameters were considered for in-depth evaluation. It was found that there is no harmful interstitial condensation and mold risk stayed at a relatively low level. However, wall orientation plays a significant role in whole year moisture accumulation dynamic.

Keywords: SIP, DEPLPHIN, hydrothermal performance, interstitial condensation.

Introduction

Structural insulated panel (SIP) is a composite building material which consists of three main layers: one core layer and two skin layers. Usually a thicker core layer is made of non-structural materials, such as extruded and expanded Polystyrene (XPS/EPS), as well as Polyurethanes (PUR) (Panjehpour et al., 2013). However, more specific materials could be found in different SIPs. For instance, in SCS (steel-concrete-steel) SIP a lightweight/normal concrete is used (Mugahed Amran et al., 2020), while for a skin layer production cement, plywood, sheet metal or oriented strand board (OSB) may be chosen. These layers are connected to each other by dint of an adhesive (Ahmad Kayello, 2018).

First introduced in North America and being quite new, this material has not yet gained a widespread recognition around the world, due to a firmly ingrained approach in housing sector in the form of timber-framed construction in current building industry. However, this is gradually changing as there is a tendency to invest in innovative solutions in order to overcome modern day challenges, and these changes make SIPs more in demand today (Harris et al., 2019).

SIPs are utilized in the construction of floors, external walls, ceilings etc., where the thickness of the insulation differs according to the needed thermal insulation value. Panels can be produced in large units with prefabricated openings for windows and doors. Then these large-sized elements are ready to be delivered directly to the construction site (Švajlenka & Kozlovská, 2022).

Like any other building material, SIP has its advantages and flaws. As it was mentioned earlier, SIPs are prefabricated structures, so they have advantages of controlled quality, reduced material losses, fast construction, less required labour and, consequently, lower total costs (Panjehpour et al., 2013). Furthermore, more classic structural insulated panels (OSB-insulation-OSB) are lightweight and have great energy performance characteristics (Phillips et al., 2021). Some of the flaws of SIP panels are as follows: a core is usually made from a non-eco-friendly artificial material, which under normal conditions is rather flammable; panels are air-impermeable, so indoor environment might be exposed to risk of high humidity level; SIPs do not have a high load-bearing capacity, therefore it is necessary to ensure a reinforcement against different kinds of loads (Mohammadabadi et al., 2021).

It is evaluated that water and the subsequent accumulation of moisture in building structure is the cause of approximately three-quarters of all building damages. Thus, the management of water in buildings is one of the most important factors affecting a building service life. There are four main mechanisms of moisture transport in buildings: vapour diffusion, air movement, capillary suction, and fluid flow (Bastien & Winther-Gaasvig, 2018). The transfer of water vapour by diffusion, which is primarily considered in scope of this paper, occurs when the difference in vapour pressure between two sides of a building structure takes place. The common practice to prevent vapour diffusion in cold climate is to add vapour barrier (or retarder) on the interior side of the insulation (Cammalleri et al., 2003).

It can be stated that unlike SIP walls, performance of widely used timber frame walls regarding a water vapour diffusion was largely investigated during past years. Numerous studies were carried out in temperate maritime climates using perspective renewable hemp-based insulation materials (Latif et al., 2014), (Latif et al., 2015). After experiments conducted in more severe climate regions, a group of Estonian researchers suggested that a wind barrier plays a crucial role in terms of condensation and mould growth risk inside a wall structure (Pihelo et al., 2016), (Pihelo & Kalamees, 2016). Obtaining similar results, Geving et all. observed no significant difference in relative humidity levels when installing vapour barriers with high (Sd = 40 m) and low (Sd = 2 m) water vapour resistance, however this requires thick (50 mm) layer of wind barrier made of wood fibre board (Geving et al., 2015). Finally, Morelli et all. came to a conclusion that generally cellulose insulation showed lower relative humidity levels than mineral wool insulation, however, depending on internal humidity classes possible safe solution for wind-vapour barrier ratio varies from 1:10 to 1:1.5 (Morelli et al., 2021).

Several studies have been conducted considering SIP-based huts exposed to Canadian Artic climate. The primary focus of these studies was the examination of attics and various SIP joints in terms of airtightness and hygrothermal performance. It has been examined that the weakest point occurred at the joint of 3 building envelope structures meet each other (for example, two aligned wall structures and a ceiling structure). Moreover, a large air leakage through such joints, where a structure highly relies on a tape seal, could be reduced intending to avoid possible condensation, snow, and frost accumulation (A Kayello et al., 2013), (Ahmad Kayello et al., 2017).

Although most often SIP building failures are related to rainwater penetration into an enclosure or warm air leakage from interior space structure, there is a hypothesis which states that under cold climate conditions wall siding could act as a vapour retarder and could initiate damaging condensation. An example of such situation was noticed in SIP walls with vinyl siding in Alaska (Trechsel et al., 2010).

So-called Glaser method, a steady-state condition principle for a prediction of a maximum interstitial condensation and annual moisture balance, is often being practiced in Latvia. Nevertheless, it is considered as an assessment method rather than precise data interpretation, that does not provide highly accurate results (BSI, 2012). The aim of this study is to apply a dynamic hygrothermal simulation approach to evaluate the reliability of utilizing a conventional wall structure in Latvian climate. The main limitation of this study is absence on national data on wind driven rain. Data from METEONORM was used for calculations. Despite the fact that many study addressed hydrothermal performance of SIP panels, there is a lack of data on such construction behavior in Baltic Climatic conditions. The practical significance of this study is data for energy auditors and engineers on sustainability of such construction. Also, study addressed evlauation of hydrothermal performances based on real measurements in bathrooms. However measurements and simulation took place for The total duration of the simulation was 19 days, this brings initial information on possible risk.

Methods

To achieve the determined goal, further dynamic hygrothermal simulations were executed in DELPHIN 6.1 software. DELPHIN is designed to simulate the combined transport of heat, air, moisture, and other penetrable matter in porous building materials. This tool is widely used in scientific community and has been validated by many researchers in their recent works (Claude et al., 2019), (Fantucci et al., 2017), (Pihelo et al., 2020), (Wang & Ge, 2018).

Unfortunately, it is challenging to acquire all necessary climate data for Latvian cities, so the outdoor climate data for the simulation of the wall in the city of Riga was obtained from Meteonorm 8.1.1 software, taking into account ambient temperature, relative humidity, wind driven rain, short wave solar radiation and sky radiation (see Fig. 1).

Fig. 1
Outdoor climate data

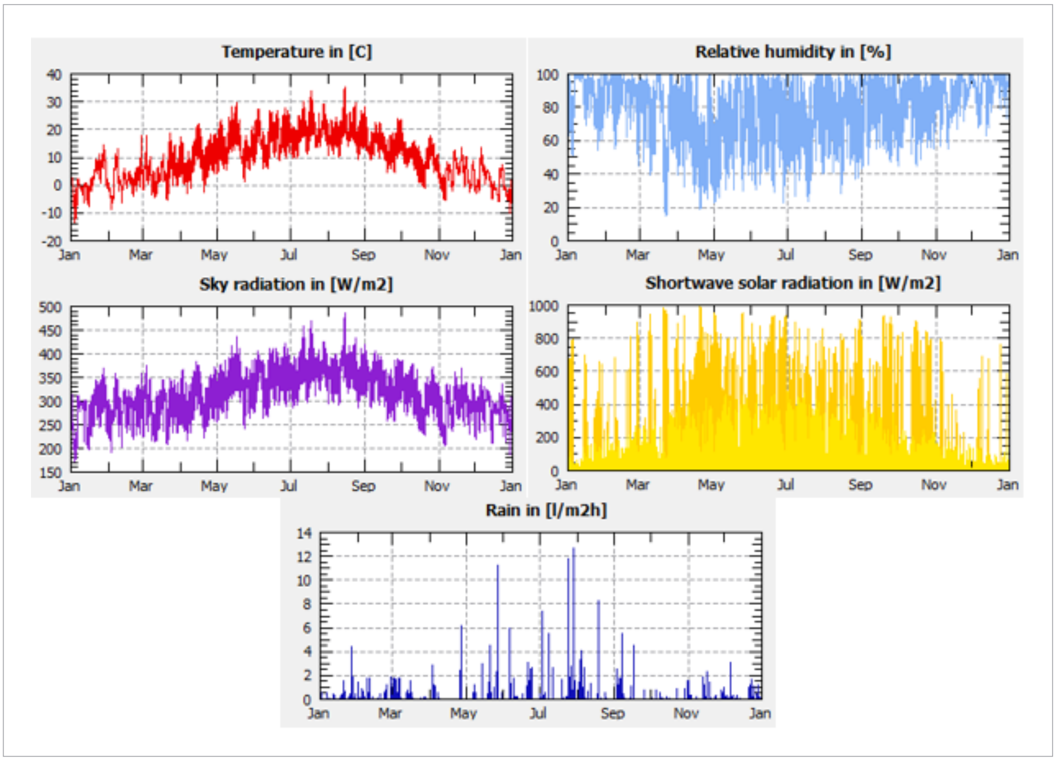
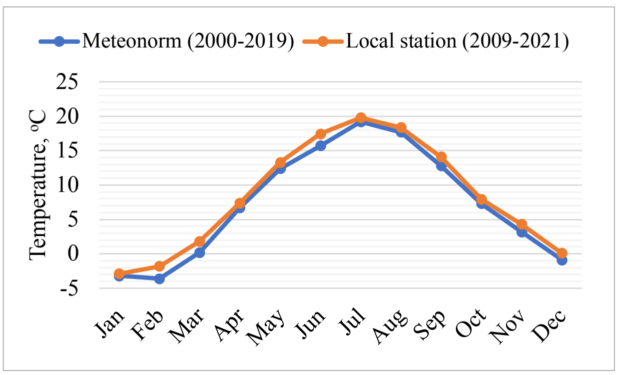


Fig. 2
Comparison of average month temperature values for Riga



With a purpose to check data from Meteonorm, it was decided to gather data from a local weather station as well. As it can be seen in Fig. 2, monthly average temperature values from Meteonorm calculated from a period of 2000-2019 were in a good agreement with the graph plotted using values from the local station. This information was found to be reliable for subsequent usage.

A wall selected for a hygrothermal analysis is not yet a very commonly applied solution for a single-family dwelling in Latvia, therefore there is a lack of experience related to performance of such a structure in the local environment. The examined wall has SIP-based structure (see **Fig. 3**) and it consists of 11-mm OSB, 180-mm EPS insulation layer, another 11-mm OSB, wind barrier (Sd = 0.02 m) and 12.5-mm cement board. Some used material properties can be found in **Table 1**, however, the wind barrier is excluded from the simulation as a material layer and appears only as an additional equivalent of air layer thickness (Sd) between external OSB and cement board.

Table 1

Properties of simulated materials

Delphin ID	Material	Bulk density, kg/m^3	Thermal conductivity, W/(m*K)	Water vapour diffusion resistance factor, -	Water uptake coefficient, kg/(m^{2}*s$^{0.5}$)
650	OSB	595.0	0.130	165	0.002
187	Expanded polystyrene board	23.0	0.036	96	0.00001
654	Cement board	1158.7	0.313	26.4	0.014

Inclination of simulated wall is 90°, orientation is 0° (north-facing wall). Initial temperature was set to 20°C, and relative humidity to 80 %.

The experiments were made in two different climates. In the beginning, the indoor climate was chosen to be calculated, based on input weather data, according to DIN EN 15026 and WTA leaflet 6.2 for increased moisture load. The range of temperature during a year is 20–25°C, the range of relative humidity levels is 35-65 %, the overall simulation lasted 3 full years. Then real measured values (specifically temperature and relative humidity, which have higher values than in the prior climate data set) from the bathroom of the apartments located in Riga were set as indoor boundary conditions. Data acquisition was executed using HOBO U12-013 data loggers from 10-th to 28-th of November with 5-minutes intervals (see **Fig. 4**). The total duration of the simulation was 19 days.

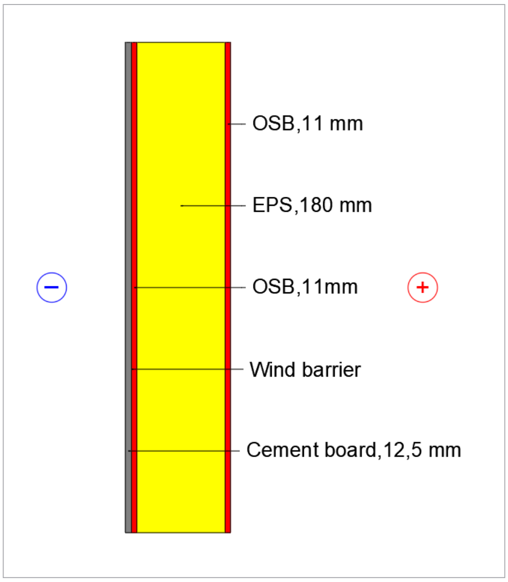


Fig. 3

Studied SIP wall

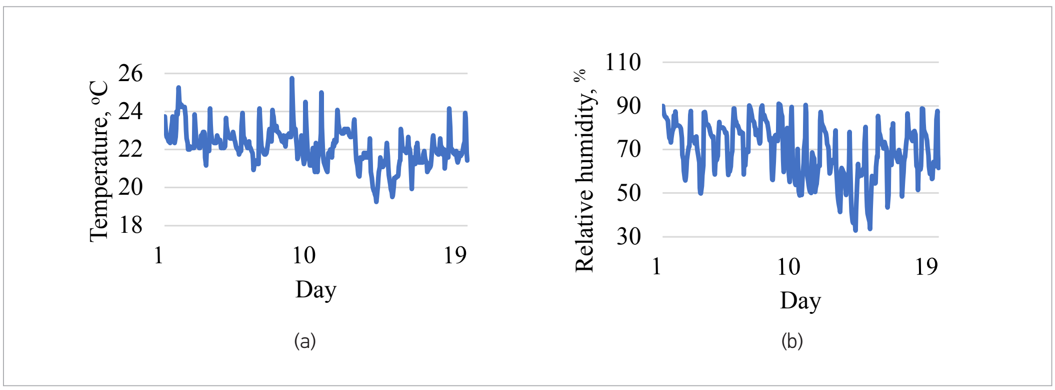


Fig. 4

Measured boundary condition data for the bathroom simulation

Since OSB is a wood-based building material, which is especially susceptible to mould and moisture damages, three 1-mm thick layers of OSB in the above-mentioned simulations were monitored: (a) layer just before EPS (closer to the inner surface), (b) layer just after EPS (closer to outer surface), (c) layer before wind barrier.

To evaluate the risk of mould growth inside the selected wall structure, the so-called VTT model, which is implemented in Delphin, is suitable. The original VTT model was created in Finland by Hukka and Vittanen (Hukka & Viitanen, 1999) and gained an extensive recognition over the years. To perform an assessment, it is necessary to set relative humidity, temperature, and specific parameters related to examined material structure. As an output, the mould index is obtained (MI, ranges from 0 to 6, that means no growth and 100 % coverage of the surface, respectively), which represents the damage of materials by mould (Fantucci et al., 2017). An interpretation and evaluation of mould growth risk based on mould index offers a traffic light classification: if no risk is presented, the traffic light remains green. This classification applies to interfaces which are not in direct contact with the inside air for MI<2 (several local mould growth colonies on surface (microscope)) that was chosen as the evaluation criterium to stay on the safe side (Viitanen et al., 2015).

Regarding the parameters needed to be determined, it was fairly noticed that mostly unclear and ambiguous suggestions exist so far (Johansson et al., 2021). For this purpose, default values from WUFI Mold Index VTT add-on for OSB were used – for this reason material type and surface type were selected to be "sensitive" to mould growth, while mould growth decline rate was set as "almost no decline".

Results and Discussion

Fig. 5 demonstrates that no condensation occurred at any time of the simulation in every controlled layer as the relative humidity level did not exceed 95 %, which is a threshold for over hygroscopic moisture defined in Delphin. Layers (b) and (c) have similar profiles, yet more pronounced

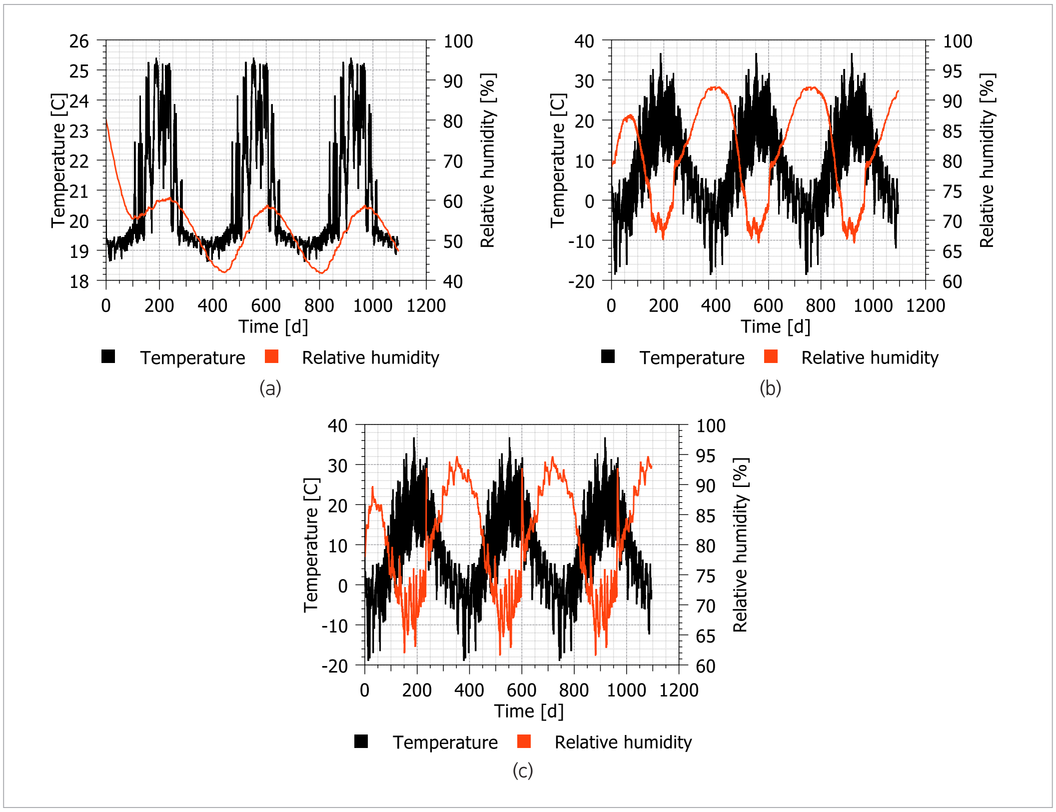


Fig. 5

Temperature and relative humidity inside examined wall within 3 years, (a) layer before EPS, (b) layer after EPS, (c) layer before wind barrier relative humidity fluctuations characterize (c) layer since it is located closer to outer surface and is exposed to outdoor climate.

Fig. 6 presents a comparison of modelling results where the two earlier defined climates were applied. The corresponding graphs of (b) and (c) layer have a quite minor diversity in both parameters. Despite this, outcome in (a) layer for bathroom climate shows greater temperatures during the whole period of simulation (that distinguishes the mentioned climate data set) and slightly higher relative humidity levels, which at the same time do not exceed 1.5 % limit, so it can be stated that in this particular situation indoor data set with increased temperature and moisture load has relatively little impact on the wall's hygrothermal performance.

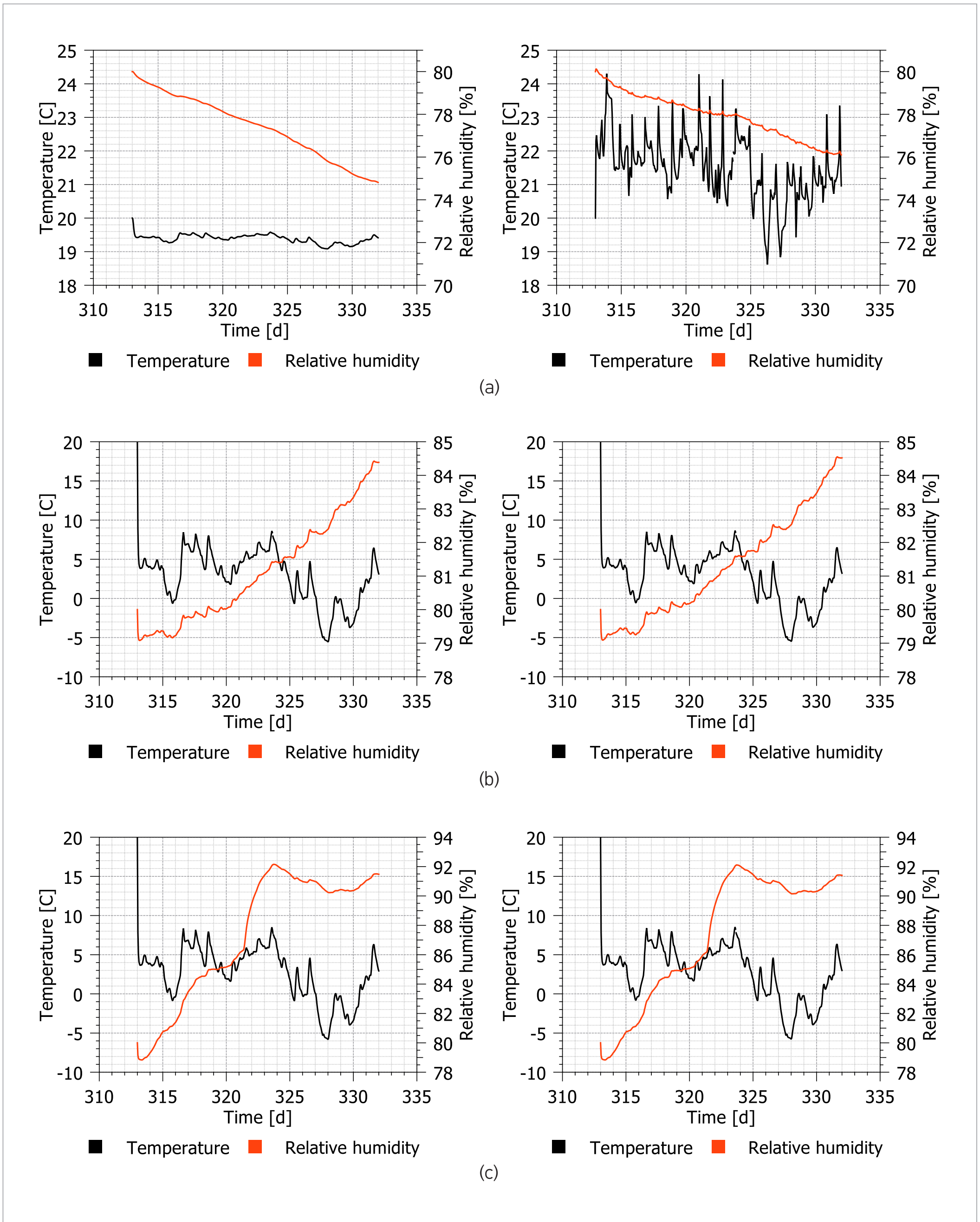


Fig. 6

Temperature and relative humidity inside examined wall from 10-th to 28-th of November: outdoor climate – DIN EN 15026 and WTA 6.2 (left), outdoor climate – measured data (right), (a) layer before EPS, (b) layer after EPS, (c) layer before wind barrier

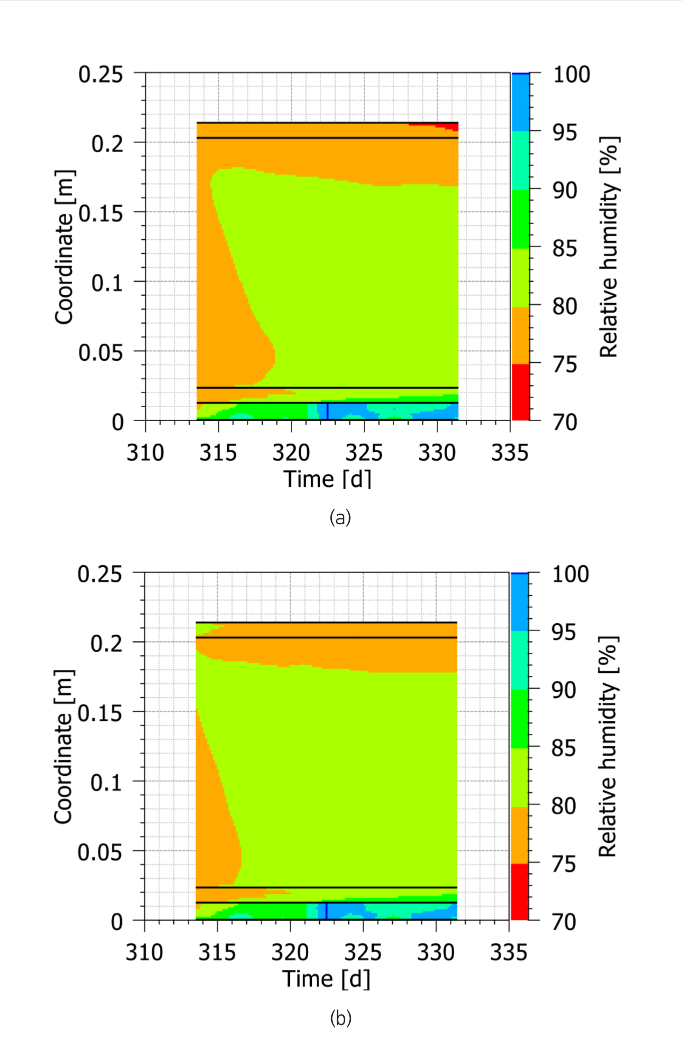


Fig. 7

Relative humidity profile of the examined wall (coordinate 0 m displays the outdoor surface), outdoor climate – DIN EN 15026 and WTA 6.2 (a), outdoor climate – measured data (b)

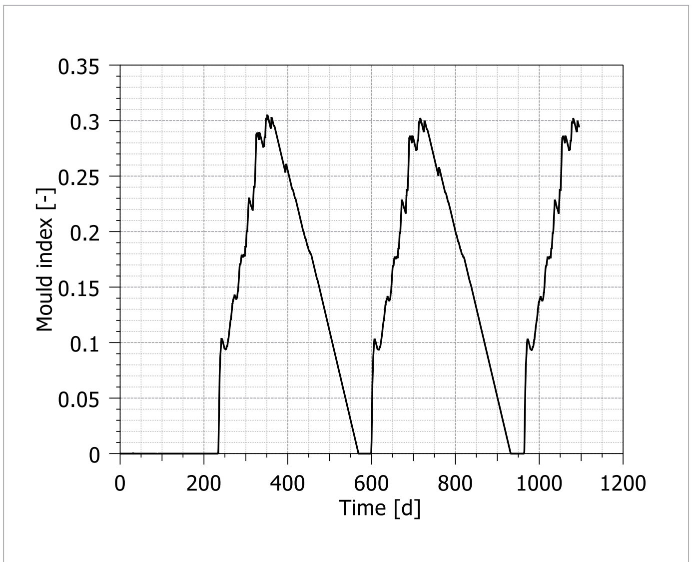


Fig. 8

VTT mould index of examined wall in (c) layer before wind barrier

According to **Fig. 7**, a short-term increase in humidity and temperature inside a thermal envelope does not affect the operation quality of the structure. The relative humidity level increased insignificantly, while condensation took place only in the cement board regardless of the provided climate. Although the mass density of condensed liquid water in the board has separate peaks during the years, the maximum reached values do not exceed 31.1 kg/m^3 and all accumulated condensate dries out in a spring-summer period (outdoor climate - DIN EN 15026 and WTA 6.2).

As expected, the most critical OSB layer with respect to possible mould growth is (c) layer (see **Fig. 8**), where the peak MI value is only 0,31, which is far from described limit of 2. It is worth noting that the graph has a stable profile, which means that it has reached the maximum MI and will not rise in future, whilst MI in (a) and (b) layer tend to be even closer to 0, hence the wall structure is assumed to be completely mould safe.

However, wall orientation plays an import role. As it can be seen from **Fig. 9**, the south oriented wall has a better drying potential.

Fig. 9 presents interface between external OSB and EPS. In case of north wall relative humidity doesn't drop below 60 %.

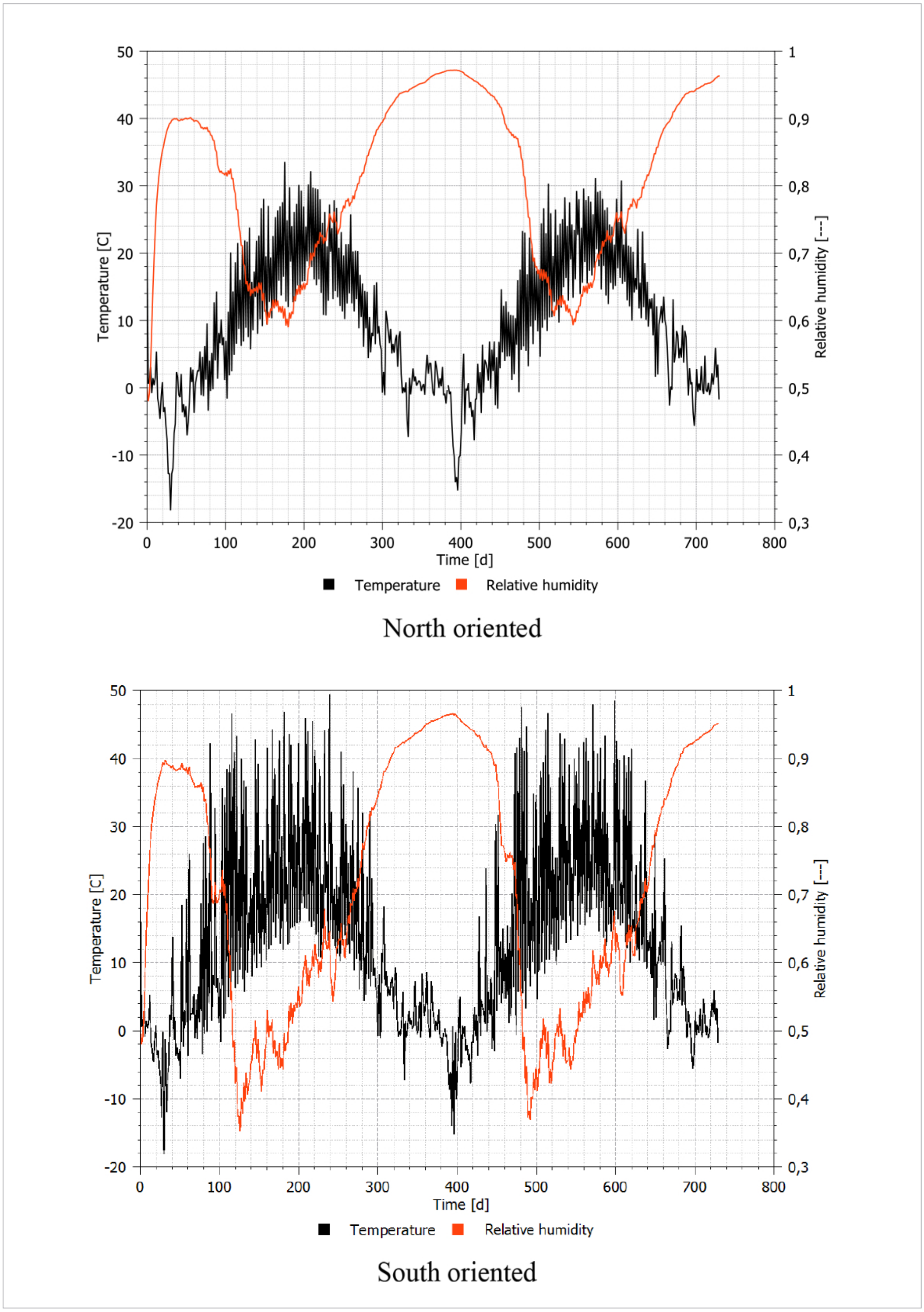


Fig. 9
Temperature and relative humidity for different wall orientation

Conclusions

In the current study, simulations of SIP wall and assessment of its hygrothermal performance in Latvian climate conditions were conducted. Results reveal that, in general, the wall appeared to be suitable for both investigated indoor climate cases. All the examined OSB layers stayed below condensation limit, which is outreached only in the outdoor cement board layer, nonetheless, even there a condensate does not accumulate and evaporates freely throughout the year. The VTT mould model also shows that there is a small and harmless amount of expected mould. In addition, it was observed that increased temperature and relative humidity levels indoors do not largely affect these parameters inside the wall – the effect evidently falls towards the outdoor surface.

In order to expand knowledge about the moisture damage resistance of SIP walls, as well as other parts of a building enclosure, and about interaction with interior spaces of increased moisture and temperature loads, further investigation should be carried out. This should include models validated by real measured data that would represent an influence of a long-term operation under simulated extreme conditions.

The SIP panels could be recommended for application in Baltic Climatic conditions. However, some extra stimulation may be required in case of north oriented wall in combination with high internal moisture loads. For example, for such premises as sauna, small SPA etc. Also, ventilation plays an important role to minimalize risks of interstitial condensation and mould growth. Future work will be focused on estimation of internal moisture loads in different type of rooms with a special focus on bathrooms.

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